



Cryogenic Propulsion Stage

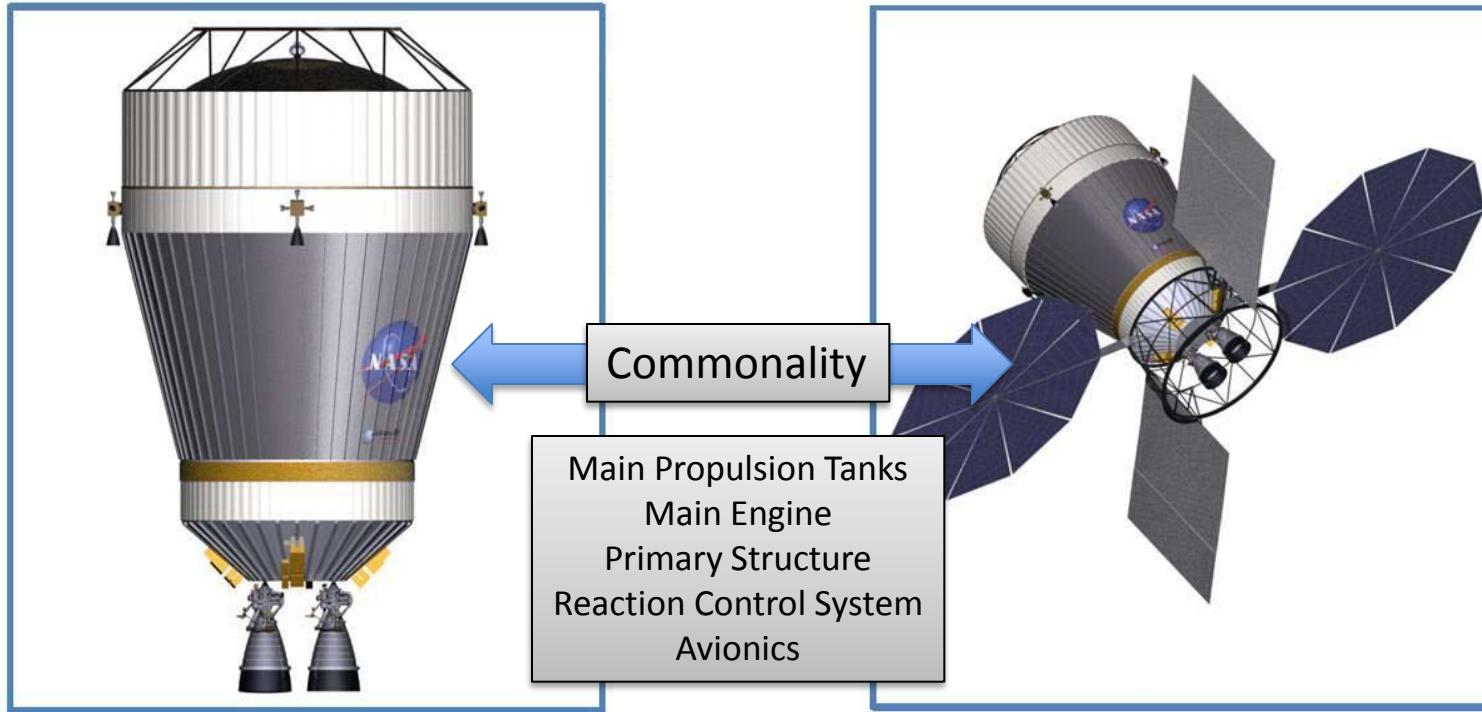
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- ◆ **The CPS is an in-space cryogenic propulsive stage based largely on state of the practice design for launch vehicle upper stages.**
 - However, unlike conventional propulsive stages, it also contains power generation and thermal control systems to limit the loss of liquid hydrogen and oxygen due to boil-off during extended in-space storage.
- ◆ **The CPS provides the necessary ΔV for rapid transfer of in-space elements to their destinations or staging points (i.e., E-M L1).**
- ◆ **The CPS is designed around a block upgrade strategy to provide maximum mission/architecture flexibility**
 - Block 1 CPS: Short duration flight times (hours), passive cryo fluid management
 - Block 2 CPS: Long duration flight times (days/weeks/months), active and passive cryo fluid management

Cryo-Propulsion Stage – Block 1, Block 2



Block 1 LOX/LH₂ Cryo Stage:

Passive Boil-Off Control
12 t inert mass
67 t propellant
2X 30,000 lbf NGE

Block 2 LOX/LH₂ Cryo Stage:

Zero Boil Off Control
21.4 t inert mass
47 t propellant
30.8% Offloaded

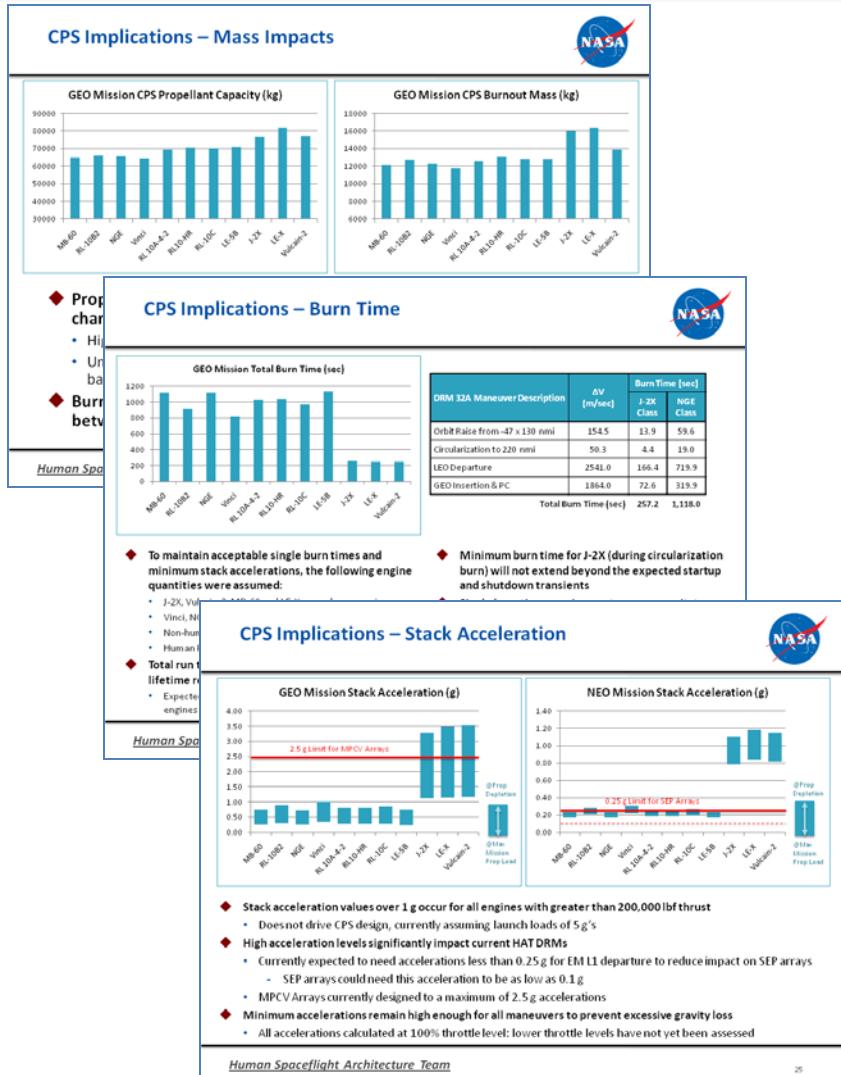


- ◆ **Using HAT Cycle B DRMs, assess implications of using various engine options**
 - High Thrust vs. Low Thrust (>200k vs <35k lbf)
 - International Engines (JAXA & ESA)
- ◆ **Top level CPS implications were assessed**
 - Propellant Mass Impacts
 - Burnout Mass Impacts
 - Burn Time – total mission run time and minimum burn time
 - Stack Acceleration – both maximum and minimum values
- ◆ **Assessment highlights the compilation of several efforts**
 - Thrust Range for CPS: J-2X vs RL10 “classes”
 - International Partnerships
 - Commonality
 - NGE Requirements

Engine Assessment Summary



- ◆ Higher thrust engines are not the preferred solution for CPS to meet the current HAT DRM requirements
 - Integrated stack accelerations greater than current HAT element limits
 - Burn times occur within known engine transients
 - Engines not currently designed for required number of restarts
 - Lower Isp results in CPS growth
- ◆ Lower thrust engines fit the current HAT DRM requirements better due to higher Isp and lower integrated stack accelerations
- ◆ Results of this assessment are preliminary
 - Any engine chosen will need a more in depth assessment to capture detailed system impacts





- ◆ **Continued effort to meet HAT mission goals and objectives**
- ◆ **Continued refinement of stage design and related sensitivities to drive out top level requirements**
 - Block 1 Duration Trade Studies
 - Power options
 - Boil-off verification/predictions
 - Continued investigation on long duration cryogenic fluid management
 - Reduced boil-off
 - Zero boil-off
 - Propulsion Trades
 - Main Propulsion
 - Reaction Control System



BACKUP

Fwd Assembly Structure/Payload Adapter

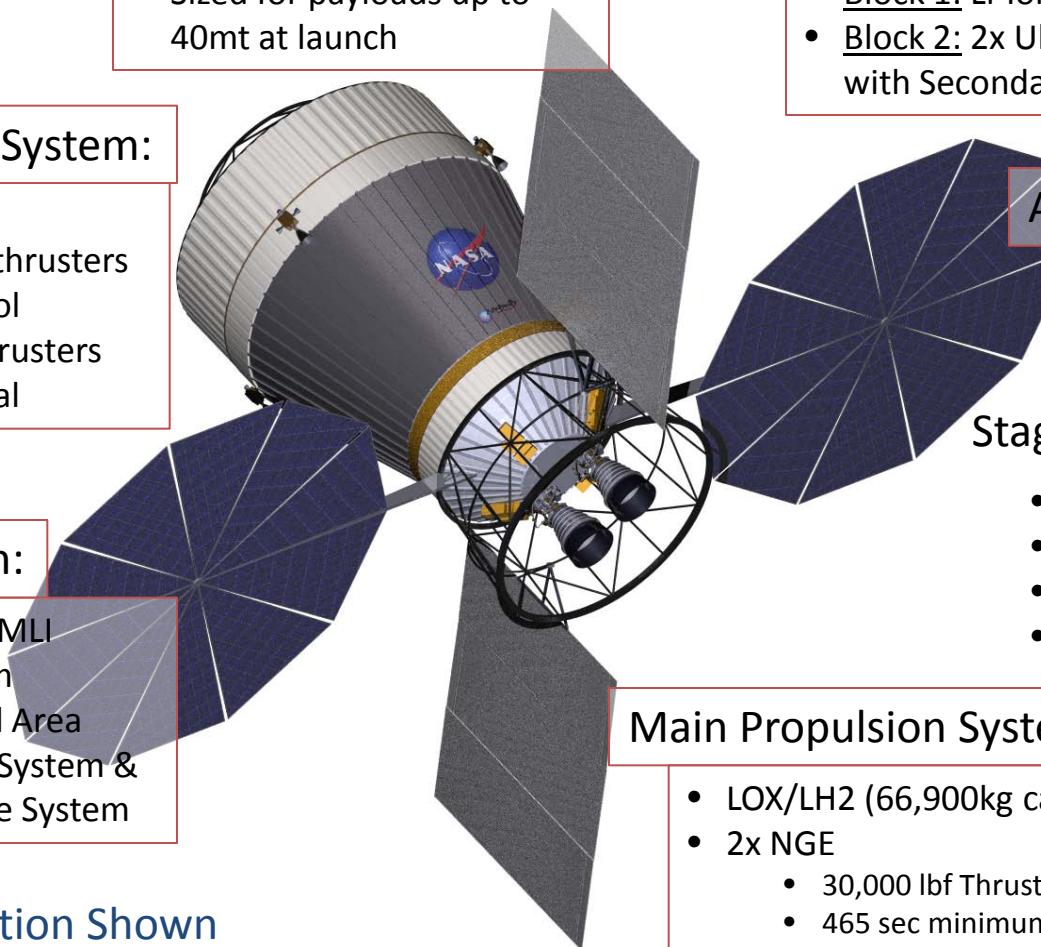
- Sized for payloads up to 40mt at launch

Reaction Control System:

- MMH/NTO
- 8x 110 lbf lateral thrusters for attitude control
- 8x 900 lbf axial thrusters for MCC & disposal

Power System:

- Block 1: Li-Ion Batteries
- Block 2: 2x UltraFlex Arrays with Secondary Batteries



Thermal System:

- Block 1: SOFI/MLI Passive System
- Block 2: Broad Area Cooler Active System & Block 1 Passive System

Block 2 Configuration Shown

Aft Assembly Structure

- Sized for thrust loads up to 75,000 lbf

Stage Characteristics:

- Diameter: 7.5 meters
- Length: 13 meters
- Array Diameter: 9.5 meters
- Array Power: ~22kW

Main Propulsion System:

- LOX/LH₂ (66,900kg capacity)
- 2x NGE
 - 30,000 lbf Thrust
 - 465 sec minimum Isp

Engine Implications



J2-X, LE-X, & Vulcain-2 (> 200 klf)

- ◆ **J2-X & Vulcain-2 is a Gas Generator cycle**
 - Isp: 438 - 448 second Range
 - Application: Boost & orbit insertion (Eg SaturnV & Ariane)
- ◆ **High stack accelerations major issue for HAT DRM elements**
- ◆ **Short burn times for small maneuvers for large engines**
 - Delta-V errors can be expected due to the majority of short maneuvers occurring within expected engine transients
 - Does not allow for engine steady state operation
 - Resulting increase in shutdown variability causes larger residuals and thrust dispersions
- ◆ **Restart capability also a potential issue with this engine class, 5 starts needed**
 - J-2X specification allows for two ignitions
 - Without redundancy 4 starts possible (Gas generator currently uses 2 of 4 cartridges per ignition)
 - 5 starts would require new ignition system
 - Vulcain-2 is a sea level engine not a in space engine
 - Requires soft goods, start transients, and re ignition system investigation/development
 - Significant development and testing may be necessary to qualify this engine for multi in space restart
 - LE-X not developed (specifications unknown)
- ◆ **Long term mission survivability risk**
 - J-2X specification does allow for space environments
 - Driving CPS duration approximately 530 days

NGE, RL10, Vinci, MBXX, LE-5B (< 30 klf)

- ◆ **RL10 and Vinci are Closed Expander cycle**
 - Isp: 450 - 465 second range
 - Application: Orbit insertion & transfer In-space (Eg Centaur)
 - Derivatives include Expander Bleed & Augmented Expander
 - Allows for Higher Isp without large nozzle extension
 - Allows for Higher Thrust as it is not heat transfer limited
- ◆ **Higher Isp reduce propellant mass & burnout mass**
 - Repeatable discreet transients due to simplicity & inherent power limits of cycle
- ◆ **Low accelerations reduce integrated stack loads for other architecture elements**
 - Throttling may be required for burns w/ SEP arrays deployed
 - Expander throttle control within previous NASA experience
- ◆ **Acceptable burn times are for these class of engines**
 - Engines less than 30k lbf thrust require more than two engines
- ◆ **Top level analysis shows multiples of all low thrust engine options fit within CPS OML**
 - Closed expander engines require nozzle extension to reach high Isp
 - Extension criticality & reliability human rating complication
 - Stack length considerations not yet addressed
 - Advanced Expander engine cycles (eg NGE & MBXX) enable high Isp within smaller real estate
- ◆ **Class of engines Designed & Qual'd for space environments & space coast**
 - Including wider inlet conditions and boost phase vibe stability

CPS Engine Options

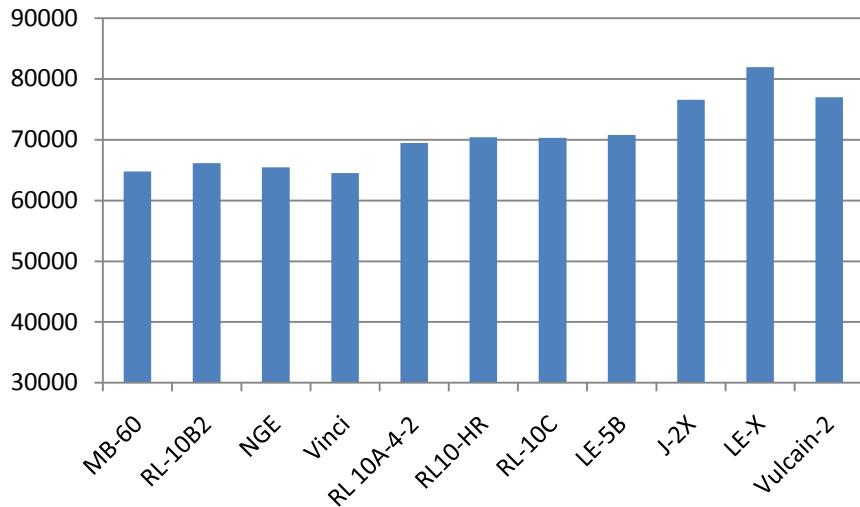


	US Engines						JAXA Engines			ESA Engines	
	NGE Requirement	J-2X	RL10 Human Rated*	RL10A4-2	RL-10B2	RL-10C -1	LE-5B	MB-60	LE-X	Vulcain-2	Vinci
Cycle Type	TBR	Open GG	Expander	Expander	Expander	Expander	Expander, H2 bleed	Expander - bleed	Expander, H2 bleed	Open GG	Expander
Vacuum Thrust, lbf	25,000-35,000	294000	16,800	22,300	24750	23900	30800	60000	317000	301243	40500
Vacuum ISP, sec	465 or greater	448	450	450.5	465.5	448.5	447	467	432	432	465
Engine Dry Mass, lbm	NTE 700	5450	419	377	668	419	628	1302	4956		352 w/o nozzle
Engine Diameter, in	NTE 73in	120	46	46	84	56.8					86
Engine Length, in	NTE 90in	185	89	89.7	163.5	87.2	111	130			164
Mixture Ratio	5.5 (adjustable)	5.5	5.35	5.35	5.88	5.88	5	5.4	5.9	6.1	5.8
Chamber Pressure	TBR	92.2 bar	~300 psia	611 psia	24 bar (633 psia)	633 psia	36bar	2015 psia		115 bar	60.8 bar
Expansion Ration	TBR	92.1	84	84	280	130	110		37	60	240
Nozzle	Fixed (preferred, but not required)	Gimbal	Fixed	Fixed	1 Fixed 2, Extendable	1 Fixed	Extension	Fixed	Fixed	Fixed	Extension
Throttle	Throttles down to 21,000 lbs or lower	Two throttle settings	Fixed Throttle	Fixed Throttle	8% - 104%	Fixed Throttle	5%-100%	scalability 35klb to 350 klb	5% - 100%		
Restartable	Minimum of 4 flight starts	Yes	yes	yes	yes	yes	yes	yes	yes	Baseline: Ground start	yes up to 5 times
Life expectancy	3000 seconds or greater	1400	2000	2000	2000	2000					

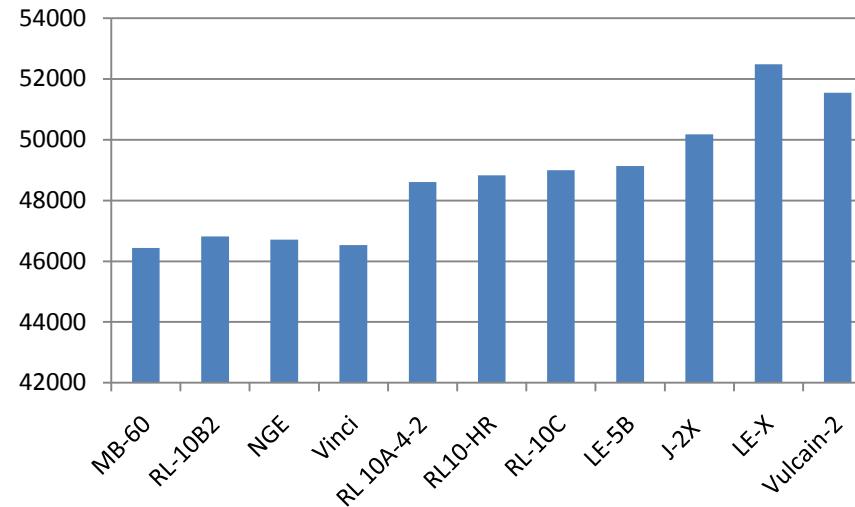
CPS Implications - Propellant Mass Needed



GEO Mission CPS Propellant Capacity (kg)



NEO Mission CPS Propellant Capacity (kg)

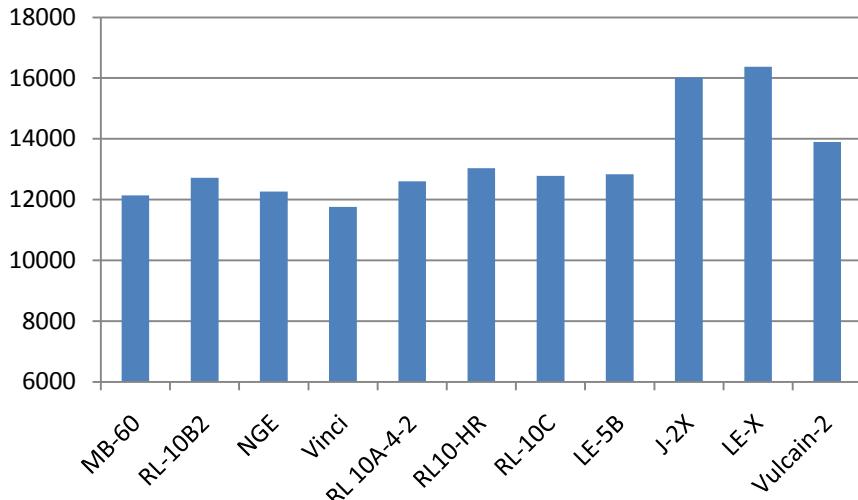


- ◆ Obvious trend shows that lower Isp engines require additional propellant
- ◆ Additional architecture analysis necessary to determine CPS propellant load that breaks current HAT DRMs

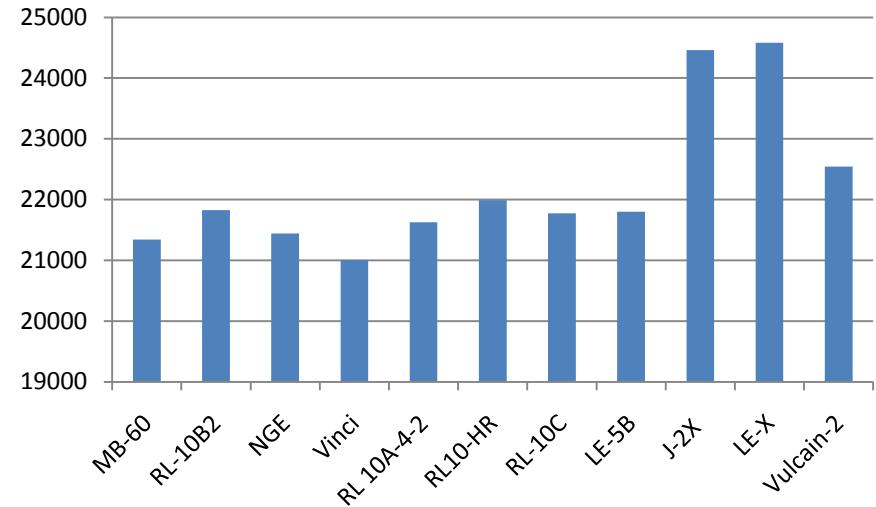
CPS Implications - Burnout Mass



GEO Mission CPS Burnout Mass (kg)



NEO Mission CPS Burnout Mass (kg)

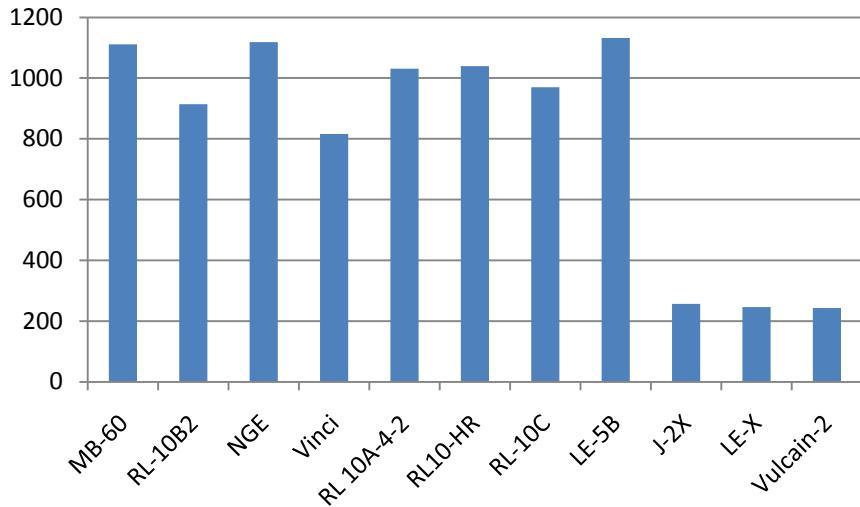


- ◆ Burnout mass differences scale with propellant load
- ◆ Minimal impacts due to engine mass
 - Currently only primary engine mass included, secondary engine hardware not modeled
- ◆ Differences in propellant load bigger mass driver than burnout mass

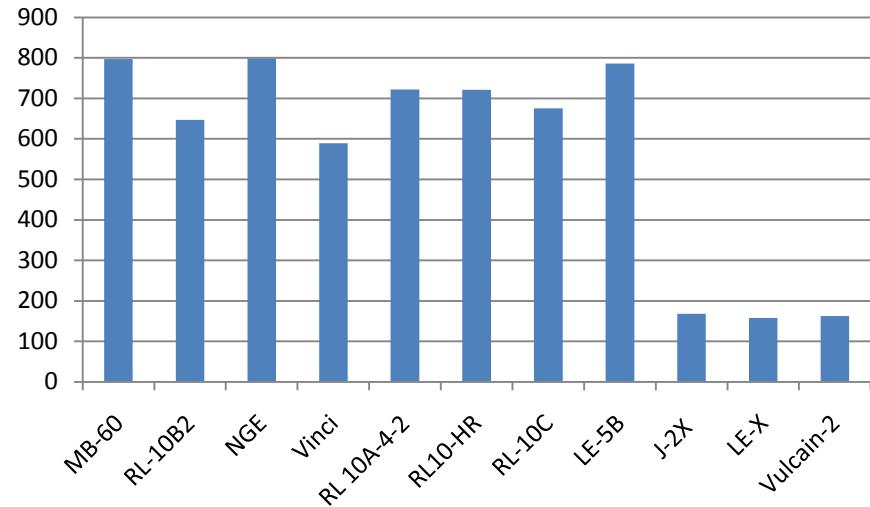
CPS Implications – Burn Time



GEO Mission Total Burn Time (sec)



NEO Mission Total Burn Time (sec)



- ◆ To maintain acceptable single burn times and minimum stack accelerations, the following engine quantities were assumed:
 - J-2X, Vulcain-2, MB-60 and LE-X use only one engine
 - Vinci, NGE and LE-5B assume two engines
 - Non-human rated RL-10 variants use three engines
 - Human Rated RL-10 uses four engines
- ◆ Total run times need to be verified against engine lifetime requirements, data not currently available for all engines

Detailed Burn Times (J-2X thrust class)



DRM 32A Maneuver Description	ΔV	Burn Time
	(m/sec)	(sec)
Orbit Raise from -47 x 130 nmi	154.5	13.9
Circularization to 220 nmi	50.3	4.4
LEO Departure	2541.0	166.4
GEO Insertion & PC	1864.0	72.6
Total Burn Time (sec)	257.2	

- ◆ **Minimum burn time for J-2X (during circularization burn) will not extend beyond the expected startup and shutdown transients**
- ◆ **Vulcain-2 and LE-X transient data not known, but behavior expected to be similar**

DRM 34B Maneuver Description	ΔV	Burn Time
	(m/sec)	(sec)
Orbit Raise from -47 x 130 nmi	154.5	13.4
Circularization to 220 nmi	50.3	4.3
EM L1 Departure	320.3	39.9
Powered Lunar Swingby	183.8	21.6
Powered Earth Swingby	869.4	89.5
Total Burn Time (sec)	168.6	

Detailed Burn Times (NGE class thrust)



DRM 32A Maneuver Description	ΔV	Burn Time
	(m/sec)	(sec)
Orbit Raise from -47 x 130 nmi	154.5	59.6
Circularization to 220 nmi	50.3	19.0
LEO Departure	2541.0	719.9
GEO Insertion & PI	1864.0	319.9
Total Burn Time (sec)		1,118.0

- ◆ **Single burn time requirement extends just beyond typical RL10 performance for GEO mission**

- 700 sec single burn for RL10

DRM 34B Maneuver Description	ΔV	Burn Time
	(m/sec)	(sec)
Orbit Raise from -47 x 130 nmi	154.5	61.9
Circularization to 220 nmi	50.3	19.7
EM L1 Departure	320.3	188.7
Powered Lunar Swingby	183.8	102.3
Powered Earth Swingby	869.4	426.0
Total Burn Time (sec)		798.2

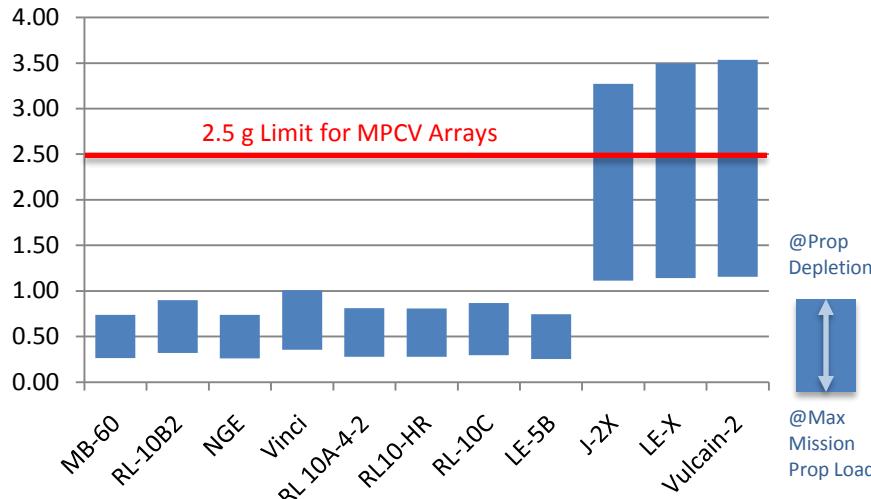
- ◆ **Single burn time requirements may necessitate additional engines for the lower thrust class engines**

- RL10 variants, LE-5B, Vinci, and MB-60

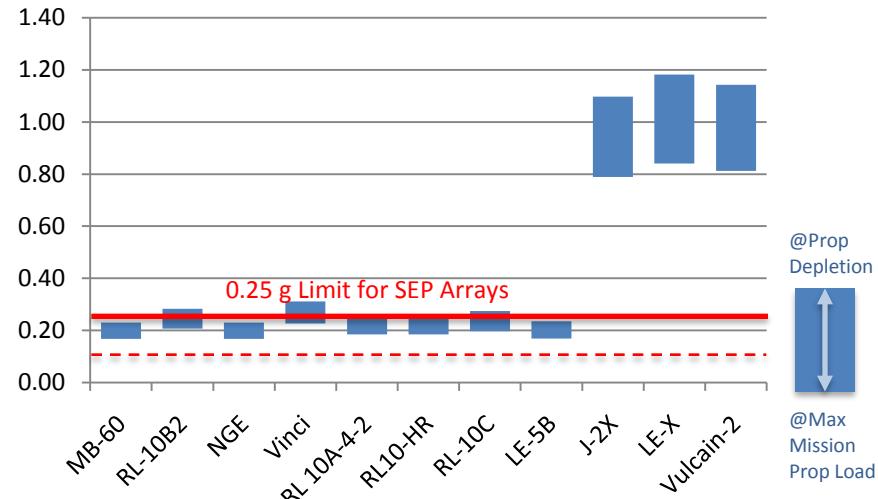
CPS Implications – Stack Acceleration



GEO Mission Stack Acceleration (g)



NEO Mission Stack Acceleration (g)



- ◆ Stack acceleration values over 1 g occur for all engines with greater than 200,000 lbf thrust
 - Does not drive CPS design, currently assuming launch loads of 5 g's
- ◆ High acceleration levels significantly impact current HAT DRMs
 - Currently expected to need accelerations less than 0.25 g for EM L1 departure to reduce impact on SEP arrays
 - SEP arrays could need this acceleration to be as low as 0.1 g
 - MPCV Arrays currently designed to a maximum of 2.5 g accelerations
- ◆ Minimum accelerations remain high enough for all maneuvers to prevent excessive gravity loss
- ◆ All accelerations calculated at 100% throttle level: lower throttle levels have not yet been assessed